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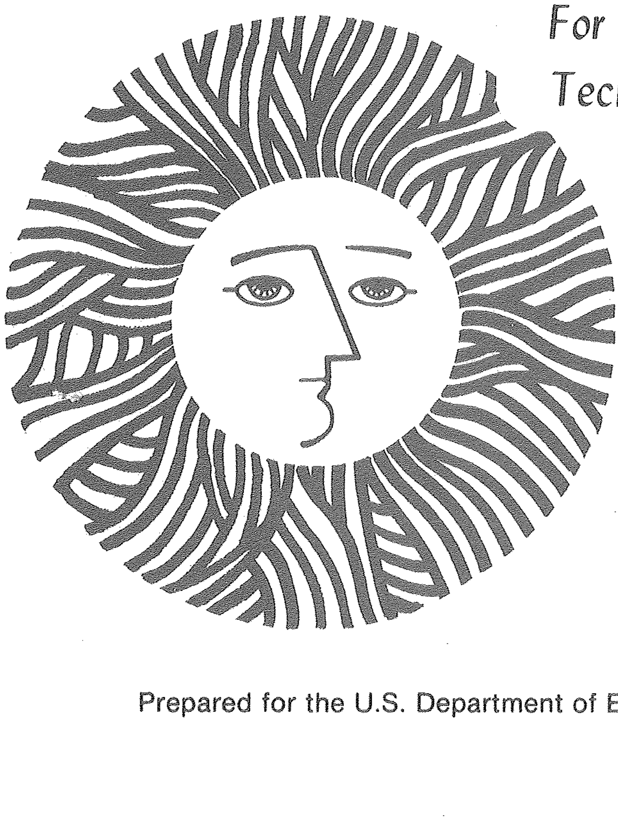

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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COST EFFECTIVENESS OF LONG LIFE INCANDESCENT LAMPS AND ENERGY BUTTONS

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April 7, 1980

The work described in this report was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Applications of the U.S. Department of Energy under contract No. W-7405-ENG-48.

ABSTRACT

Long-life replacement lamps for the incandescent lamp have been evaluated with regard to their cost effectiveness. The replacements include the use of energy buttons that extend lamp life as well as an adaptive fluorescent circline lamp that will fit into existing incandescent lamp sockets. The initial, operating, and replacement costs for one million lumen hours are determined for each lamp system. We find the most important component lighting cost is the operating cost. Using lamps that are less efficient or devices that cause lamps to operate less efficiently are not cost-effective. The adaptive fluorescent circline lamp, even at an initial unit cost of $20.00, is the most cost-effective source of illumination compared to the incandescent lamp and lamp systems examined.

1. INTRODUCTION

Industrial, commercial and residential consumers have been trying to reduce spiraling costs by lowering their energy consumption, one of the major contributors to these increases. Lighting is one area that is being scrutinized, particularly in spaces that have been over-illuminated.

One current vogue of amending the illumination excess has been to remove lamps as well as replace existing fixtures with lower wattage lamps. Toward this end, the lamp industry has produced incandescent lamp replacements that use less energy, provide less illumination and extend lamp life. The longer lamp life helps to reduce the labor cost for replacing lamps that are in continuous use and require frequent replacement.

This report is concerned with the relative merits of these products. Of particular interest in this study is the performance of lamps used in conjunction with devices used to extend lamp's life, generally described as "energy buttons."

Energy buttons are placed into light bulb sockets (Edison sockets) and the lamp inserted into the socket over the button. This is schematically illustrated in Fig. 1, which also shows the circuit diagram where the button is in series with the lamp. The energy buttons use either one of two types of solid state devices.

One type of device is a thermistor (at normal temperatures the thermistor has high resistance and its resistance decreases as the thermistor's temperature is increased). When the lamp is turned on the initial current is less than the operating current since the thermistor's resistance is high. After several minutes the circuit current heats the thermistor, reducing its resistance, and the circuit current increases. The lamp then operates near its normal light output. Energy button manufacturers contend that starting incandescent lamps in this manner extends the lamp's life by a factor of four.

The second type of energy button device is a diode. The diode device rectifies the 60Hz input power, reducing the power available to the lamp by about one-half. This lowers the filament temperature of the lamp, thus reducing the light output and extending lamp life.

In the following sections we will review the performance of these long-life light bulbs and measure the performance of incandescent lamps with and without energy buttons. We will analyze the total cost of all these light sources by considering the initial cost, the operating cost and the labor replacement cost. This result will assist consumers in selecting the most cost-effective light source suitable for their needs.

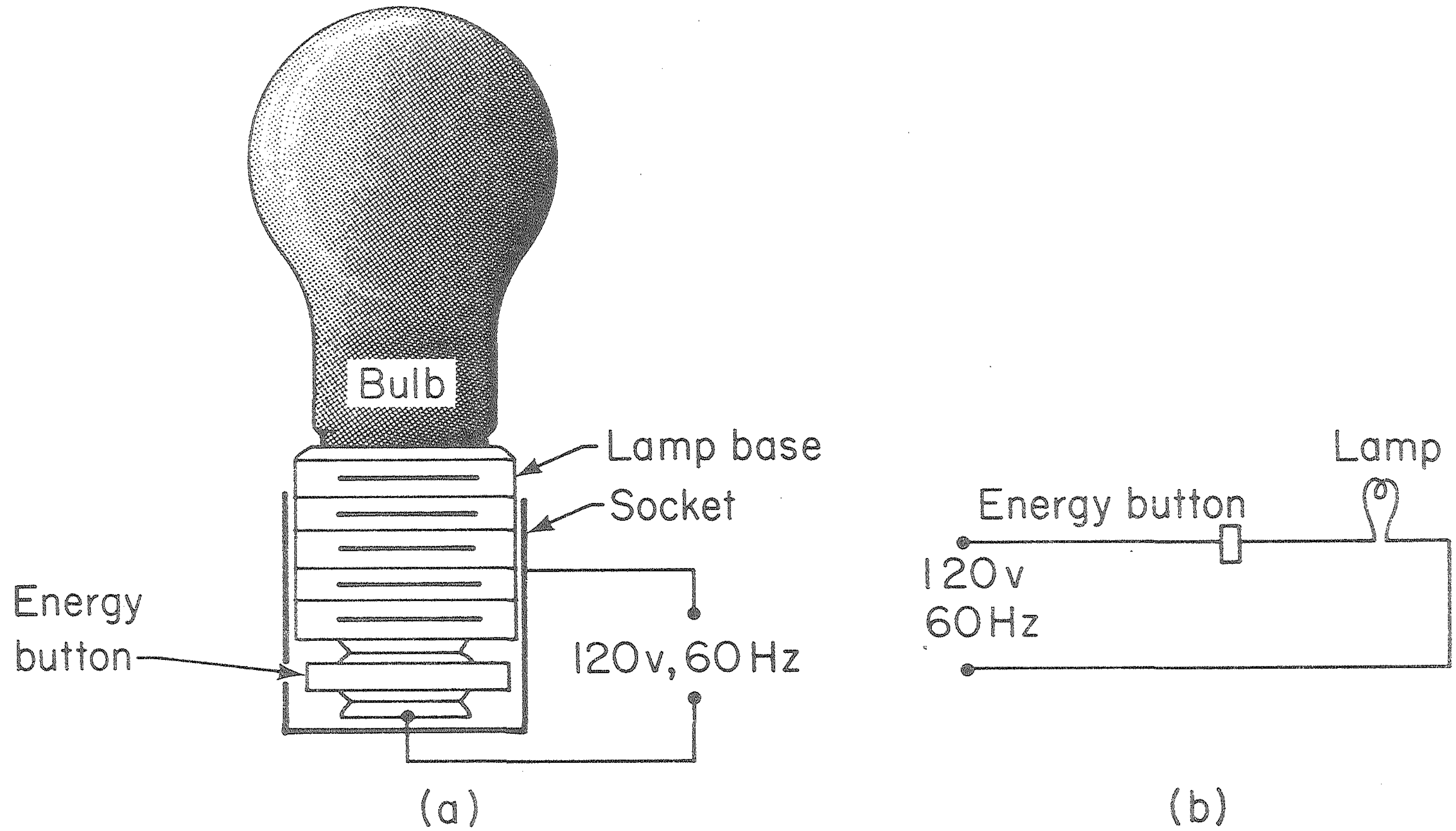

Figure 1. Energy Button in the lamp socket, (a) and in the lamp circuit (b).

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2. MEASUREMENTS

The performance of a light source is determined by measuring the input power supplied to the lamp or lamp system and the total light flux radiated by the lamp. Efficacy is the figure of merit and is defined as the ratio of the light flux to the input power (lumens per watt). One standard method used to measure the total light flux from a light source is with an integrating sphere[1] and a standard light source with a known light output. In this study we have used an integrating light chamber to determine the light flux from the lamps. We have employed a 100 watt incandescent lamp as a standard (rated light output = 1750 lumens), and measured the relative changes of the other lamps with respect to this lamp.

Estimating the relative light output of two light sources with the naked eye will give an erroneous result because the eye is sensitive only to brightness differences (contrast), not the amount of light.

The electrical input (power, voltage and current) to each lamp and lamp system was measured at the same time the light flux was measured in the integrating chamber. In order to obtain the most reliable results, the same 100 watt incandescent lamp that was used as the standard was also used with the energy button. Thus, the relative changes in the efficacy with and without the button will be accurate.

We are also interested in identifying any potential safety hazard and have measured the socket temperature of the 100 watt lamp with and without the thermistor type of energy device.

3. RESULTS

3.1 Performance

In Table 3.1 we present the results of our input-output measurements for the 100 watt lamp, the 100 watt lamp with each type of energy button, a 100 watt (130 volt) lamp, a 100 watt long life lamp and an adaptive circline fluorescent lamp. The adaptive circline fluorescent lamp can be inserted into the same Edison type socket that is used for the incandescent lamp.

The results show that the diode type energy buttons reduce the input power to the 100 watt incandescent lamp by 42 percent; however, the light output of the lamp decreases by 74 percent. The lamp efficacy is the best figure of merit to assess the lamp's performance. Note that all the long-life lamp systems operate at efficacies less

1. Kaufman, J. E., Editor, Illuminating Engineering Society Handbook, 5th Edition, Waverly Press, Baltimore, MD, 1972 (pp 4-9).

TABLE 3.1

LAMP PERFORMANCE

	Lamp Type						
	100 Watt Lamp	40 Watt Lamp	100 Watt Lamp (130 volt)	100 Watt Lamp (long life)	100 Watt Lamp (diode)	100 Watt Lamp (thermistor)	Fluorescent Lamp (adaptive)
Input Voltage (volts)	120	120	120	120	120	120	120
current (amps)	.833	.337	.750	.833	.705	.832	.560
Power (watts)	100	40.2	90	100	58.5	100	44
Output Light (lumens	1750	470	1350	1490	490	1601	1750
Change Output Light (%)*	0	-74	-23	-15	-73	-10	0
Efficacy (lumens/watt)	17.5	11.7	15.0	14.9	8.3	16.0	39.8
Change in Efficacy (%)*	0	-33	-14	-15	-53	-9	+127

*Relative change with respect to 100 watt lamp.

than the 100 watt lamp and the system efficacy for the adaptive circline fluorescent lamp is 39.8 lumens per watt.

3.2 Socket Temperature

Table 3.2 lists the measured socket temperature for the 100 watt incandescent lamp and the same lamp with the thermistor type energy button. The energy button heats up when current is flowing and we find that the bulb socket reaches 105°C, compared with 48°C for the 100 watt incandescent lamp without an energy button.

4. LAMP LIFE, EFFICACY, COLOR

The results of our measurements can be understood by a brief description of the physics of the incandescent lamp. The incandescent lamp is an inefficient source of visible radiation since only a small portion of the emitted radiation is in the visible region. Most of the emitted radiation is in the lower energy portion (the near infrared). When the filament temperature is lowered, the leading edge of the emitted spectrum in the visible region shifts toward lower energy (toward the red region). There is a greater relative decrease of the radiation in the visible region, thus, the lamp efficacy (efficiency of transforming the electrical energy into light) will decrease. Due to the above shift in the spectrum for the lower filament temperature, the color of the lamp will appear more reddish.

Lamp filaments eventually fail due to the evaporation of the metal and subsequent disintegration of the filament coils. Lamps operating at lower filament temperatures have a slower evaporation rate, thus such filaments should have an extended life; however, filaments also become brittle as they operate and become increasingly sensitive to physical shock and vibration. A lamp may fail, therefore, long before its expected life due to its mechanical environment rather than because of filament evaporation. In addition to operating filaments at a lower temperature, commercial long-life lamps are filled with a heavier gas (krypton) that also inhibits the rate of evaporation of the filaments.

The above description is consistent with our measurements which show that a forty percent decrease in power results in a 75 percent decrease in light output for an incandescent lamp. This is contrary to some of the published information by some energy button manufacturers which shows that the input power and light output decrease by the same proportion.

TABLE 3.2

SOCKET TEMPERATURE

Type Lamp	Socket Temperature*
100 watt lamp	48°C
100 watt lamp with thermistor	105°C

*Ambient temperature 22°C

5. COST OF LIGHT SOURCE

In order to assess the true cost of a light source one must evaluate the lamp performance. One metric to assess the relative merits of light sources is to determine the cost with respect to a specific number of lumen hours (luminous energy). That is, we must remember when we buy a lamp we are purchasing illumination (light) and once the lamp is purchased we are committed to the cost of putting the lamp in the socket and the cost of energy until it fails. Thus, we must compare costs on a "per unit of light" basis. In the following sections we will discuss the cost of lamps with respect to one million lumen hours (10^6 l-hrs.) of light.

5.1 Lamp Life

One expression for estimating the life of an incandescent lamp operated at different voltages is the following[2]:

$$\frac{L_1}{L_0} = \frac{(V_0)^{13}}{(V_1)^{13}} \quad , \qquad (1)$$

where L_0 and V_0 are the rated lamp life and operating voltage, respectively, and L_1 is the life of the lamp when it operated at voltage V_1.

In Table 5.1 we list the rated and operating voltages of six light sources. For the lamps in the first four columns we have used the expression (1) to calculate the approximated life with respect to the 100 watt lamp L_0 (L_0 = 750 hours).

The effective lamp voltage used for the diode energy button (83 volts) was obtained by dividing the measured power by the measured current (58.5 watts .705 amps = 83 volts). Since the relative lamp lives for the long-life incandescent and the fluorescent lamp are not based upon the operating voltage rating, we have used the manufacturer's rated life. The long-life lamp is rated to operate at 120 volts but its life is extended by the use of a thicker, heavier filament and back-filling the lamp with a heavy krypton gas.

The estimated relative life of the lamp with the thermistor type energy button is calculated to be 1.56 longer. This is based upon the lamp operating at 4.2 volts less due to the voltage drop across the thermistor. The button manufacturers claim life is extended due to the method of turning on the lamp at a lower initial current. There is no evidence presented to substantiate these claims. It is possible lamp life is slightly extended by this "softer" start only near end

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2. Kaufman, J. E., Editor, Illuminating Engineering Society Handbook, 5th Edition, Waverly Press, Baltimore, MD, 1972 (pg 8-8).

TABLE 5.1

LAMP LIFE

	Lamp Type					
	100 Watt	100 Watt (130 volt)	100 Watt (thermistor)	100 Watt (diode)	100 Watt (long life)	Fluorescent Lamp
Rated voltage (volts)	120	130	120	120	120	120
Operating lamp voltage (volts)	120	120	115.8	83	120	120
Lamp Life (relative)[*]	120	2.82	1.56(3)	122(50)	3.33	13.33
Lamp Life (hours)	750	2115	2250	37,500[‡]	2500[†]	7,500[†]

[*] Relative to 100 watt lamp

[†] Manufacturer rated life

[‡] The theoretical value of life ratings become progressively less reliable once incandescent lamps are operated below 10 percent of their rated voltage.

of life when the filament is highly stressed. Due to this uncertainty we arbitrarily double the estimated life calculated from equation (1). We will assume the thermistor energy button extends the life of an incandescent lamp by a factor of three.

The theoretical extension of lamp life with the diode energy button of 122 times the normal lamp life is extremely long (750 x 122 = 91,500 hours). Even in the most intensively used areas (≈ 4,000 hours per year), a light bulb would last twenty years. This long life is difficult to substantiate. However, for such a long life, other factors would become effective in limiting lamp life, e.g., gas leakage, thermal stresses, material aging, accidental breakage, filament fatigue and filament failure due to constant vibrations. Thus, we will assume that the diode energy button will extend the lamp life by a factor of fifty.

Both of the estimates of the extended lamp life with the energy buttons have been generous to present the best possible performance of these systems.

5.2 Lamp Cost per One Million Lumen Hours

Table 5.2 lists the initial product cost for the lamps and the energy button. The prices are those specified by their manufacturer. The two prices listed for the diode type energy button are obtained from two manufacturers. We will assume an energy button will last for five lamps. They should last forever, but there will be losses during the installation, etc. The fourth column lists the unit cost for each type of light source. The final column lists the initial cost for each system for one million lumen hours. This is calculated from the following expression:

$$\text{Cost per } 10^6 \text{ lumen hours} = \frac{\text{Unit cost (\$)}}{\text{light output (l)} \times \text{life (hrs)}} \times 10^6 \qquad (2)$$

life = 750 hours x relative lamp life (see Table 5.1). Note the additional cost for the diode energy button is only about two cents since the lamp life is so long. Thus, the assumption that the buttons last for five lamp lives is not of significance. The table shows that the initial cost per 10^6 lumen hours of the 100 watt lamp and the fluorescent circline lamp are the highest. The initial cost of the 100 watt, 130 volt lamp and the 100 watt lamp with the energy buttons are the lowest.

TABLE 5.2

INITIAL PRODUCT COST

Lamp Type	Lamp (unit)	Energy Button Unit	Energy Button Per 5 Lamps	System Cost Per 10^6 l-hrs.
100 watt	\$ 0.70	\$ 0.00	\$ 0.00	\$ 0.532
100 watt (130 volt)	0.70	0.00	0.00	0.14
100 watt (thermistor)	0.70	2.00	0.40	0.31
100 watt (diode)	0.70	2.00 6.00	0.40 1.20	0.06 0.103
100 watt (long life)	0.83	0.00	0.00	0.222
Fluorescent (lamp and ballast combination)	20.00	0.00	0.00	1.600

5.2.1 Operating Cost

Table 5.3 lists the operating cost of each of the six lamp systems considered in this report. The operating cost per one million lumen hours is obtained from the following expression:

Operating Cost per 10^6 lumen hrs.

$$= \frac{\text{power (watts) x energy cost (\$/w hours)}}{\text{light output (lumen)}} 10^6 \qquad (3)$$

$$= \frac{\text{energy cost}}{\frac{\text{light output}}{\text{power}}} \times 10^6$$

Note that the operating cost of any light source depends only upon the cost of energy and the efficacy of the lamp system. The highest operating cost is obtained for the 100 watt lamp operated with the diode energy button. The lowest operating cost is obtained for the fluorescent circline system.

5.2.2 Labor Replacement Cost

The cost of replacing an incandescent lamp can vary considerably. In the home, the cost of replacement will be virtually nil, while in the commercial and industrial sectors a typical cost is about one dollar. However, there are some special locations where lamp change costs can reach several dollars. Manufacturers of long-life lamps and lamp systems (energy buttons) cite costs as high as $15.00. In Table 5.4 we have accommodated all of the claims by determining the labor replacement cost per one million lumen hours for a replacement cost from $0.10 to $15.00 for each change. This has been calculated from the expression:

Replacement Cost per 10^6 lumen hours =

$$\frac{\text{cost of one change (\$)}}{\text{light output (lumens) x Lamp Life (hrs)}} \times 10^6 \qquad (4)$$

The results clearly show that the maintenance cost per million lumen hours is least for the longer life lamps.

5.2.3 Total Cost

Table 5.5 lists the total cost of the six lamp systems by summing the three component costs. In the table there are a range of costs depending upon the labor cost of each change.

The table clearly shows that the cost of illumination is primarily determined by the <u>operating cost</u>. That is, for all lamp systems, at least one half of <u>the total cost</u> is the operating cost. The only exception is for the 100 watt lamp in which the cost of replacing a

TABLE 5.3

OPERATING COST*

	Power (watts)	Light (lumens)	Cost per 10^6 l-hrs.
100 watt	100	1750	$ 3.43
100 watt (130 volt)	90	1350	4.00
100 watt (thermistor)	100	1600	3.75
100 watt (diode)	60	490	7.35
100 watt (long life)	100	1490	4.02
Fluorescent	44	1750	1.51

*Energy cost at 0.06 per kilowatt hour.

TABLE 5.4

LABOR REPLACEMENT COST

	Lamp Changes Per 10^6 1-hrs.	Cost of Change per 10^6 1-hrs. $0.10 Per Change	$1.00 Per Change	$5.00 Per Change	$15.00 Per Change
100 watt	.76	.08	.76	3.80	11.40
100 watt (130 volt)	.20	.02	.20	1.00	3.00
100 watt (thermistor)	.28	.03	.28	1.40	4.20
100 watt (diode)	.054	.01	.05	.25	.75
100 watt (long life)	.27	.03	.27	1.35	4.05
Fluorescent	.08	.01	.08	.40	1.20

TABLE 5.5

TOTAL COST

	Initial ($) Per 10^6 l-hrs.	Operating ($) Per 10^6 l-hrs.	Total Cost per 10^7 l-hrs.			
			$0.10 Per Change	$1.00 Per Change	$5.00 Per Change	$15.00 Per Change
100 watt	.532	3.43	4.04	4.72	7.76	15.36
100 watt (130 volt)	.14	4.00	4.16	4.34	5.14	7.14
100 watt (thermistor)	.310	3.75	4.08	4.34	5.46	8.26
100 watt (diode)	.08	7.35	7.44	7.48	7.68	8.93
100 watt (Long Life)	.22	4.02	4.27	4.51	5.59	8.29
Fluorescent	1.60	1.51	3.12	3.19	3.51	4.31

lamp is between $5.00 and $15.00. For replacement costs of one dollar or less, there is little difference in cost between a one hundred watt lamp and the long-life lamp. The one exception is the lamp with the diode energy button where the high operating cost of $7.43 overshadows its very low initial and replacement cost. The most cost-effective incandescent lamp system is the 100 watt, 130 volt lamp in applications where the cost to change lamps is more than a few cents.

The most interesting outcome of this comparison of light sources is the extraordinarily low cost of the adaptive fluorescent circline lamp system. Even for the relatively high initial unit cost of $20.00, the total cost of this light source is less than one half the cost of most of the alternatives considered in this report for all of the replacement costs.

6. SAFETY

The energy button does present a potential safety hazard both in its installation and during operation.

The manner in which the energy button is installed poses a potential shock hazard. Since the installer is not certain whether the electrical power is off or on, he may be subject to a serious shock. Granted it is due to the installer's carelessness, but one is still subject to injury. In addition, Edison sockets that are horizontal, or burn lamps base-up, pose a further installation difficulty.

In many sockets, the energy buttons constrain the depth at which the lamp can be inserted. Thus, the electrical live portion of the lamp base protrudes above the socket. Accidental contact with this portion and with an electrical ground can result in a serious shock.

Finally, the measurement of the higher socket temperature for the thermistor energy button and 100 watt lamp (see Table 3.2) presents a potential fire hazard. While the 105°C temperature does not exceed the UL safety code, some lamps may be used in enclosed fixtures that have no ventilation; in these applications a safe socket temperature could be exceeded resulting in a fire.

In the use of the energy button, the above three safety hazards must be recognized and avoided by the personnel that install or handle this equipment.

7. CONCLUSION

Light sources that can be employed in the same application must be assessed on total cost for the light delivered. The long-life lamps examined in this report show that the operating cost is the most important factor that will establish the cost effectiveness of a light source.

Energy buttons that drastically reduce the light output and the lamp efficacy, are not cost effective even if the lamps last fifty times longer and the labor cost for each change is fifteen dollars.

The use of the 100 watt, 130 volt, incandescent lamp is the best incandescent lamp replacement for the standard 100 watt (120 volt), incandescent lamp, where the maintenance cost of replacement exceeds one dollar per change.

The most cost-effective long-life replacement lamp for the standard 100 watt (120 volt) incandescent lamp is the adaptive fluorescent circline lamp. The cost of light with this source is more than twice as cost-effective as any long-life incandescent lamp or system evaluated in this report.